Development and analysis of a novel multi-generation system fueled by biogas with smart heat recovery

Maryam Hasanzade[1], Milad Feili [2], Hadi Ghaebi [3*]

[1,2,3] Department of Mechanical Engineering, University of Mohaghegh Ardabili

ABSTRACT

This paper presents a novel multi-generation system based on biogas fuel for simultaneous production of goods such as electricity, cooling, freshwater, and hydrogen using smart heat recovery of combustion gases. The performance of the proposed system is investigated in terms of the first and second laws of thermodynamics. Also, to acquire a comprehensive evaluation of operation costs, an exergoeconomic analysis has been performed. Furthermore, a comprehensive parametric study has been conducted to understand the behavior of the system performance parameters with the design parameters. In the following, to show the superiority of using a Stirling engine, the investigation of the present study is performed under two different scenarios. The proposed system could produce 986 kW, 137.5 kW, 8.39 m^3/h, and 2.96 kg/h, net output electricity, cooling load, distilled water, and hydrogen while working with the Stirling engine. In this case, the energy and exergy efficiencies of the proposed system are obtained at 37.3% and 32.08%, which are improved by about 2.96% and 7.89%, respectively. In terms of cost metrics, the total unit cost of the products is about 0.1086$/kWh which has increased by 8.1% compared to the non-sterling engine mode.

KEYWORDS:

Gas turbine, biogas, west heat recovery, multi-generation, Stirling engine

[*] Corresponding Author: Email: hghaebi@uma.ac.ir

1. Introduction

In recent decades, the increasing growth of energy consumption such as fossil fuel energy and consequently the increment in environmental pollutants has led to the use of new methods of energy production based on waste heat recovery [1]. One practical solution is to integrate industrial processes or combine power plant cycles. In addition to reducing energy consumption, this method also reduces the emission of pollutants, increases systems' efficiency, and lowers exergy losses through heat recovery [2]. By applying waste heat recovery technology and combing energy systems, valuable forms of energy such as electricity, refrigeration, pure water, and so on can be produced. Waste heat recycling severely depends on the hot steam temperature and the intelligent selection of subsystems. The gas turbine cycle is one of the most reliable electricity generation systems due to the unit's simplicity and start-up time, and rapid shutdown. This unit has weak performance from the second law viewpoint because of the high exergy loss rate through exhaust gas. The exhaust gas temperature of the gas turbine cycle cycle is about 450-600 ° C, so there is a high thermal potential that can be used in various fields in addition to preventing environmental pollution by improving system performance from the perspective of the first and second laws. With this in mind, it seems that by using the appropriate subsystem, a significant part of exhaust gas temperature can be recycled to produce various commodities and prevent environmental issues simultaneously.

This study proposes a new multi-generation system based on a biomass gas turbine-driven cycle. Using the smart heat recovery through the intelligent selection of subsystems, the hot temperature of exhaust gas is recovered several times. This process dramatically improves the thermal and exergy efficiency of the gas turbine cycle and drastically reduces exergy losses. The subsystems of the devised multi-generation system consist of a Stirling engine, modified organic Rankine cycle, absorption cooling cycle, proton exchange membrane electrolyzer, and a reverse osmosis desalination unit. The performance of the proposed system is investigated in terms of the first and second laws of thermodynamics. Furthermore, to acquire a comprehensive evaluation of operation costs, an exergoeconomic analysis has been performed. Moreover, a comprehensive parametric study has been conducted to understand the behavior of the system performance parameters with the design parameters. The present study was conducted in two scenarios to show the superiority of using a Stirling engine, including a Stirling engine, and without a Stirling engine.

2. Methodology

Fig.1 shows the schematic of the new multi-generation setup based on the gas turbine cycle. Accordingly, the turbine's exhaust gas first enters the air-preheater (the first heat recovery step). Then flows into the Stirling engine (second step of heat recovery). The cooled gas enters the Rankine power cycle and the absorption cooling cycle. Finally, exhaust gas goes to the electrolyzer heat exchanger to produce hydrogen as the last heat recovery step. It is worth noting that the electricities required for desalination and hydrogen production are provided by the Stirling engine and Rankine power cycle, respectively.

3. Governing Equations

A thermodynamic code is developed in engineering equation solver software to simulate the proposed multi-generation system. The first and second laws of thermodynamics in terms of mass, energy, exergy, and cost balances are used in the present study as follows [3]:

$$\sum_i \dot{m}_{in} = \sum_O \dot{m}_{out} \tag{1}$$

$$\dot{Q}_{c.v} - \dot{W}_{c.v} = \sum (\dot{m}h)_{out} - \sum (\dot{m}h)_{in} \tag{2}$$

$$\dot{E}x_{D,k} = \sum_{i=1}^{k} \dot{E}x_{in,i} - \sum_{i=1}^{k} \dot{E}x_{out,i} \tag{3}$$

$$\dot{C}_{Q,k} + \sum \dot{C}_{in,k} + \dot{Z}_k = \dot{C}_{W,k} + \sum \dot{C}_{out,k} \tag{4}$$

Using the above formulations, each component of the proposed system is analyzed, and finally, the amounts of generated commodities are obtained.

The overall performance metrics parameters, including Energy, exergy efficiencies, and unit productions cost of the new devised multi-generation setup, are articulated respectively as:

$$\eta_{en,ccp} = \frac{\dot{Q}_{eva1} + \dot{Q}_{eva2} + \dot{W}_{net}}{\dot{Q}_{AVG} + \dot{Q}_{VG}} \tag{5}$$

$$\eta_{ex,ccp} = \frac{\dot{W}_{net} + \left(\dot{E}x_{28} - \dot{E}x_{27}\right) + \left(\dot{E}x_{30} - \dot{E}x_{29}\right)}{\dot{E}x_1 - \dot{E}x_3} \tag{6}$$

$$TUCP = (\dot{C}_{w,net} + \dot{C}_{12} + \dot{C}_{41} + \dot{C}_{35}) / (\dot{W}_{net} + \dot{E}x_{12} + \dot{E}x_{41} + (\dot{E}x_{35} - \dot{E}x_{34})) \tag{7}$$

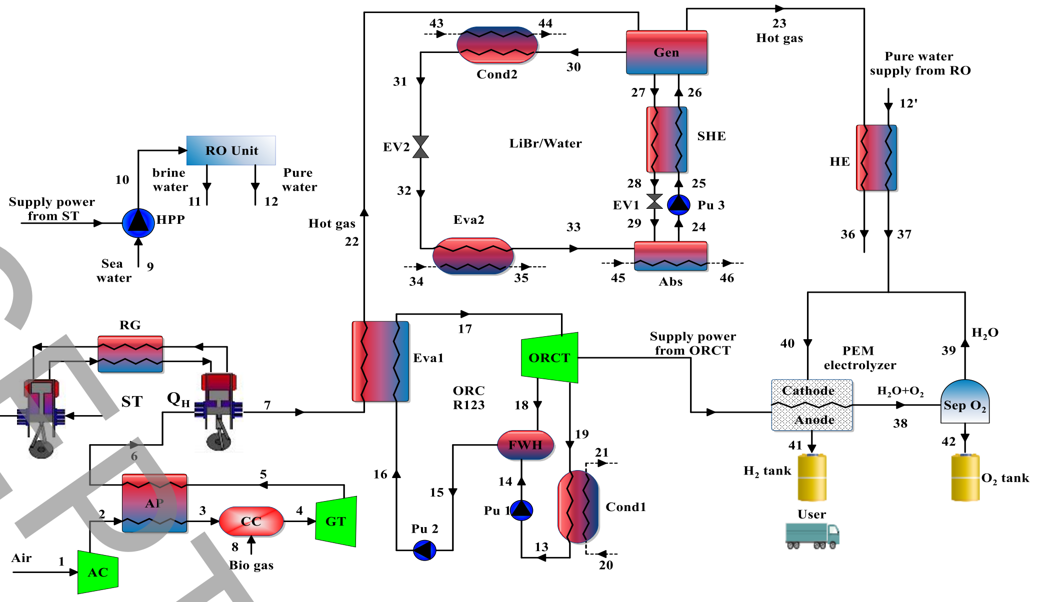

Figure1. The layout of the new devised biomass-driven multi-generation system

4. Results and Discussion

Table 1 presents the main decisive factors of the proposed system for two scenarios to show the impact of using a sterling engine on the proposed system. Accordingly, while operating with the sterling engine, the gas turbine produces about 2469 kW of electricity, of which the air compressor consumes 1469 kW. Meanwhile, the Stirling engine is capable of producing 35.55 kW, which is used to supply electricity to the desalination unit and produces 8.39 m^3/h of pure water. In addition, in this case, Rankin power cycle generates 212.9 kW of electricity and supplies electricity to the PEME unit. Overall, the proposed system is capable of producing 986 kW of net electricity and 137.5 kW of cooling load by the absorption cooling cycle. All the mentioned products have finally resulted in achieving 37.3% and 32.07% energy and exergy efficiency. In contrast, when the system operates without a Stirling engine, the amount of electricity generated and consumed by the gas turbine and air compressor remains constant. However, the gas turbine supplies the electricity required for the RO unit's high-pressure pump and reduces the system's net electricity by 35.6 kW. Subsequently, the Rankin power cycle and absorption cooling cycle capacities increase due to receiving more energy from the exhaust gas. At the same time, the electricity consumption of their pumps is increasing. Totaly, In this case, the energy and exergy efficiency of the system has decreased by 2.94% and 7.89% due to the reduction of net electricity generation. Also, the system's investment cost has been reduced from 49.29$/h to $ 47.13$/h due to the lack of cost related to the purchase of the Stirling engine. Finally, due to the reduction in electricity and freshwater costs, the total unit cost of products has decreased from 0.1086 $/kWh to 0.0998 $/kWh

Table1. Main performance factors for different mixtures

Performance	With sterling engine mode	Non-sterling engine mode
$\dot{W}_{AC}$(kW)	1469	1469
$\dot{W}_{GT}$(kW)	2469	2469
P_{ST}(kW)	35.55	-
$\dot{W}_{ORCT}$(kW)	212.9	225.2
$\dot{W}_{net}$(kW)	986	950.4
$\dot{Q}_{eva2}$(kW)	137.5	140.5
$\dot{m}_{dw}$(m^3/h)	8.39	8.39
$\dot{m}_{41}$(kg/h)	2.96	2.96
$\dot{E}x_{Fu}$(kW)	3403	3403
$\dot{E}x_{D}$(kW)	2269	2303
$\dot{E}x_{L}$(kW)	42.93	94
$\dot{E}x_{Pr}$(kW)	1091	1006
η_{energy}(%)	37.3	36.2
η_{exergy}(%)	32.07	29.54
$\dot{Z}_{net}$($/h)	49.29	47.13
$TUCP$($/kWh)	0.1086	0.0998

5. Conclusions

This survey develops a novel biomass-based multi-generation system with smart heat recovery. The main conclusions of the present study are as follows:

A) The designed system produces 986 kW, 137.5 kW, 8.39 m^3/h, and 2.96 kg/h net electricity, cooling load, pure water, and hydrogen, respectively. B) without a Stirling engine, net electricity generation, energy, and exergy efficiency values declined about 35.55 kW, 2.94%, and 7.89%, respectively. C) Utilizing a Stirling engine has significantly reduced the exergy associated with destruction and loss.

6. References

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